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A Résumé of a Paper by H. R. Ricardo

From "The Automobile Engineer," April, 1927

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SOME NOTES ON GASOLINE-ENGINE DEVELOPMENT

A Résumé of a Paper by H. R. Ricardo.*

The goal for which we are constantly striving is the improvement of the high-speed engine and the evaluation of its various compromises. The main difficulty is the maintenance of a true sense of proportion. We want an engine which shall have a good performance in every sense of the term, including silence, smooth running, and durability. It must also be efficient in relation not only to the fuel it consumes, but also to the material of which it is made, which is often equally important. In this connection we may assess the useful life of a high-speed engine to-day as somewhere about five years, since even though at the end of this period it will probably still be running as well as ever, improvement to-day is so rapid that it will by then be superannuated. Taken by and large, the first cost of an engine and that of the fuel it consumes in five years is pretty nearly the same in the case of a touring car and in the ratio of about 1 : 5 in the case of a commercial vehicle. In the case of the touring car, therefore, a saving of 10 per cent in fuel consumption is not worth having on economic grounds if it adds 10 per cent to the cost of the engine, and improvement in fuel economy and reduction in first cost are

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therefore of about equal importance economically; while in the case of the commercial vehicle it is worth adding up to 50 per cent to the cost of the engine to effect a saving of 10 per cent in fuel economy. As a broad generalization, to save material we must increase the speed, but only up to the limit at which we can still use the ordinary materials of commerce and the ordinary limits of accuracy. To economize fuel we must use the highest possible ratio of compression but, again, only up to the limit at which we can still use the ordinary fuels available. Gasoline dopes and fancy steels are valuable as means of enabling us to explore further afield, but the author would contend that no designer should rely on using either; we should rely only on the use of the cheapest materials and the most widely distributed fuels, and make the most of these. With modern methods of manufacture the cheapest engine is not necessarily the lightest, but rather that which is produced from the least weight of raw material. Multiplicity of parts, provided these parts are small and not unduly intricate, does not necessarily involve expense.

Stiffness rather than strength is the dominating consideration throughout, and that stiffness must be sought not by sheer mass, but rather by judicious distribution of material.

There is a very prevalent and widespread belief that the use of a high compression necessarily entails both rough running and overheating; there can be no greater fallacy. Let us

differentiate most emphatically between a high compression ratio and too high a compression resulting in detonation. So long as we rigidly keep clear of detonation, then the higher the compression the cooler will the engine run, for the simple reason that for the same power we shall require much less total potential heat energy and, at the same time, we shall be turning a greater proportion of it into useful work.

The curve (Fig. 1) shows the variation in power, in fuel economy, and in heat-flow over the range of compression from 3.5 : 1 to 7.0 : 1 taken on a fuel that does not detonate over this range; from this it will be seen that the surplus heat-flow, more particularly the temperature of the exhaust valve, diminishes very rapidly with increase of compression. Moreover, as the efficiency is improved the temperature of the surplus heat becomes lower and its destructive capacity is therefore reduced. So soon, however, as detonation becomes apparent, the whole picture is changed at once, and the heat-flow rises with appalling rapidity. We must therefore first ensure absolutely that there shall be no persistent detonation under any normal condition of running. Occasional slight detonation under conditions of extreme aggravation does not matter, though even that should be avoidable.

We can suppress detonation by:

(1) The use of metallic dopes in small quantities, such as lead ethide, iron carbonyl, etc.

(2) The use in considerable quantities of fuel of high ignition point, such as benzol and other aromatics, naphthenes, alcohol, etc.

(3) The design of the combustion chamber.

The first expedient may, in the author's opinion, be ruled out altogether except for purely "stunt" purposes. All the organic metallic dopes are expensive, poisonous, and more or less deleterious to the engine, and the increase in efficiency resulting from their use is more than offset by the cost, danger, and trouble which they involve.

The second expedient is now common practice. Led by the Shell Company, all the oil companies now so blend their fuels as to maintain a uniform and fairly high proportion of aromatics and naphthenes - at all events, on the European market. Differences, of course, still exist, depending upon the sources of supply available to the different oil companies, but they are nothing like so great as formerly; and, compared with seven years ago, a designer may now rely safely on using a compression at least half a ratio higher, thanks to the improvement in the fuel alone.

In the author's experience, the widest scope of all lies in the direction of the third expedient, thanks to the greatly increased knowledge of the process of combustion and the application of this knowledge to the design of the combustion chamber.

In this connection it may not be without interest to describe some experiments which we have been making, partly at the suggestion of Mr. H. L. Horning, of the Waukesha Motor Company, with a side-by-side valve engine having a detachable cylinder head so arranged that we can very readily fit a test head of any reasonable shape. A row of six quartz windows is placed across the head, radiating at equal intervals from the sparking plug. These quartz windows are masked by a large rotating disc driven through helical gearing from the camshaft and having six narrow slots. The phase relation of the disc can be varied at will by the operator, and is shown by an index dial. A Farnborough indicator is connected also with the cylinder head, so that the pressure rise and its phase relation can be observed at the same time. Figs. 2 and 3 show the apparatus used. The operation of the plant is as follows:

The engine is run at full load on a certain predetermined mixture strength and with the spark set to give maximum power. To check exactly the time of the spark, a paper strip is pasted round the flywheel and the spark is allowed occasionally to pass through a pointer to the flywheel, thus perforating the paper and so recording exactly the ignition timing. When steady running conditions have been obtained, the operator adjusts the phase of the stroboscope disc until he can just see the flame appearing in the first quartz window adjacent to the sparking-plug. Under these conditions the first window is lit

up by a blue flame, while all the others are in darkness. This point having been ascertained, he reads off the timing on the stroboscope dial. Next he proceeds to retard the phase until flame appears in the second window, and so on until at last all six windows are showing a luminous flame. Simultaneously, another operator takes a series usually of eight or ten indicator diagrams of the pressure changes.

We have now recorded, simultaneously, the movement of the flame front across the combustion chamber and the corresponding pressure-rise. The stroboscope readings of flame spread may be taken as accurate to within plus or minus 0.5 degree, and the indicator readings of pressure-rise are of about the same order of accuracy so far as relative readings are concerned, though the absolute phase relation of any indicator is always a matter of some uncertainty. Table I gives a typical series of results from a fairly conventional type of cylinder head.

TABLE I.

Head	Brake mean pressure, lb. per sq.in.	Indicated mean pressure, lb. per sq.in.	Brake fuel consumption, pints per B.HP. per hour	Indicated fuel consumption pints per I.HP. per hour	Friction mean pressur, lb. per sq.in.	Maximum pressure lb. per sq.in.		Pressure-rise lb. per sq.in. per degree		Highest useful compression	Spark advance required at max. power mixture, degrees
						Maximum power mixture	Correct mixture	Maximum power mixture	Correct mixture		
1	108.6	121.8	.551	.483	13.2	424	378	23.6	18.0	5.2	11.5
3	105.1	118.7	.567	.489	13.6	429	389	38.5	25.6	6.8	9.5
6	107.2	120.2	.546	.478	13.5	461	417	34.1	28.7	5.37	10.0

Sight holes

Spark – 1	1 – 2	2 – 3	3 – 4	4 – 5	5 – 6
Degrees					
14.05	5.9	2.25	2.7	2.95	3.4
11.1	3.9	2.8	1.0	1.8	4.1
11.8	3.6	1.3	1.1	3.7	4.0

When detonation occurs a bright flash appears almost simultaneously in all six quartz windows, and, as showing that it does not take place until the flame has reached the very last window, it is generally observed that when the phase relation is advanced so that the flame front has only reached say, five of the windows, no trace of detonation flash can be seen, proving that even heavy detonation occurs only near the extreme end of the flame travel.

A conventional type of head was fitted in the first instance, and a very thorough investigation extending over many weeks was carried out on it with a view to learning as much as possible of the behavior of the whole plant and to determining the most significant tests to be made, and also to lay down the best course of procedure. Since then nearly thirty different heads, all of the same compression-ratio, namely, 5.0 : 1, have been tested, and with some very striking results. To determine accurately the relative tendency of various forms of combustion chamber to detonate, the composition of the fuel was varied until detonation could just be produced under certain standard conditions as to spark advance, mixture strength, temperature, speed, etc. Having found a fuel mixture which, under these standard conditions, would just detonate, this mixture was then tested in our variable-compression engine and its detonation value carefully ascertained. As illustrating the wide differences between various shapes of combustion chamber on the same engine under

identical conditions, we have found that, referred to our variable-compression engine, the highest useful compression-ratios of the various heads tested have ranged from 4.8 : 1 to as high as 6.5 : 1 referred to Shell No. 1 fuel as standard - an extraordinarily wide variation, all the more so considering that none of the heads tested were designed to have a low detonation value. It would have been easy enough to fit a head which would have detonated even below 4.0 : 1; in fact, some of the engines we have had sent to us for test have detonated at considerably more than a whole ratio less than our variable-compression engine. It would seem, therefore, that there is far more to be done by studying the shape of the combustion chamber than by any doping of the fuel or other known means, with the added advantage that shape costs nothing and is ubiquitous. With but few exceptions, all the different forms of heads we have yet tested have behaved perfectly rationally and have fulfilled our predictions, while the initial pause and subsequent rapid spread of the flame are just what are to be expected.

That the use of a high compression-ratio must necessarily involve harsh or rough running is another fallacy. Roughness, as ordinarily meant - a harsh feeling and a general tendency to cause drumming of the bodywork, etc. - is dependent, on the one hand, on the beam stiffness of the engine as a whole and of the crank shaft in particular, and, on the other hand, on the rate of pressure-rise. The author is satisfied that the actual maximum pressure has little or no effect on roughness, provided

that it is not built up too rapidly. As we increase the ratio of compression we increase, of course, the maximum pressure, and, other things being equal, we increase also the rate of pressure-rise, since combustion becomes more rapid as the density of the charge increases. If we merely increase compression without taking any steps to control the rate of pressure-rise, we shall get both higher maximum pressures and a more rapid rate of rise, as shown by the indicator diagrams in Fig. 9, taken from our variable-compression engine at ratios of 4, 5, and 6 : 1 and, under such conditions, the running certainly will be much rougher. To-day, however, we can claim to have the rate of pressure-rise under complete control, and although in slowing down the rate we shall lose a trifle in efficiency, the loss is insignificant by comparison with the large gain we shall derive from the use of a higher compression-ratio. Just recently also we have had another research engine running, in which the maximum pressure was as high as 1100 lb. per sq.in., and in which we could readily control the rate of burning. With the same compression-ratio and the same maximum pressure we could vary the rate of burning and so completely transform the character of the engine from one of the very smoothest running we have ever had to one so rough and harsh as to be almost intolerable, and that without varying the power or consumption by more than 2 or 3 per cent. In this case we were operating on the Diesel cycle - a cycle which has the advantage that the rate of burning can be

controlled at will over a very wide range.

Valve Position

The author has expressed his views fairly frequently as to the question of valve position and performance. Quite recently we have carried out two series of tests with almost identical engines of the same bore, one with side-by-side valves, and the other with overhead valves, all other conditions such as valve sizes, cam shafts, compression-ratio, valve timing, etc., being identical. Both engines had detachable cylinder heads, and both had the most efficient form of combustion chamber we could devise for either type. The performance of each engine was identical on every point, in fact, the two torque-curve tracings could be laid one on top of the other and they varied by barely the thickness of a line.

There was, however, markedly less tendency to detonate in the case of the side-by-side valve engine, due to the more central position of the sparking plug, and experiments with fuel mixtures showed that for equal tendency to detonate the compression might have been nearly half a ratio higher in the side-by-side valve engine, which would have given about 6 per cent improvement in all-round performance. In this case the author would emphasize that we employed the most suitable shape of head we could devise in each instance.

The conclusions may be summarized briefly as follows:

(1) Provided that the stroke is not abnormally short, the side-by-side valve engine will, at the same compression-ratio, give an exactly similar performance to the overhead valve push-rod type.

(2) Owing to the more central position of the sparking-plug, the side-by-side valve engine will stand a higher compression-ratio than the overhead-valve engine without detonation, and therefore will, in practice, give a better performance.

(3) To compensate for the more attenuated shape of the combustion chamber, a somewhat higher degree of turbulence must be employed for equal performance - this appears to involve a slightly more rapid pressure-rise, and therefore, for equal stiffness, it is apt to be a little rougher running. The author is not, however, at all satisfied that this disability can not be overcome.

(4) While it is easy to produce a reasonably efficient combustion chamber for an overhead-valve engine, it is terribly easy to come hopelessly to grief in the case of the side-by-side valve engine. The author has come to the conclusion, therefore, that the relative popularity of the overhead-valve engine is due to the fact

that the inexperienced designer feels that he is on much safer ground with this type.

(5) The loss of heat to the walls of the combustion chamber during combustion and expansion is, at moderate or high speeds, so small as to be relatively insignificant. The low efficiency usually associated with an attenuated form of combustion chamber is due to stagnation rather than to the high surface/volume ratio.

When a very short stroke is employed, the combustion chamber, in a side-by-side valve engine, becomes very shallow, and it is then difficult to fulfill all the requisite conditions. Moreover, the mechanical difficulties in the way of using side-by-side valves with a very short stroke, such as the fouling of the cam shaft by the connecting rod big ends and the very cramped space for tappet adjustment, are all arguments in favor of the overhead-valve arrangement for small engines or those of very short stroke. Apart, however, from this qualification, all, or almost all, the advantages would appear to lie with the side-by-side valve type of engine, which is cheaper, cleaner and more accessible.

The above remarks refer, of course, to the push-rod type of overhead-valve engine, and naturally do not apply to engines with two overhead cam shafts and central ignition, which is an almost ideal arrangement from the point of view of performance,

but is costly, elaborate and noisy.

Supercharging

There has arisen during the last few years a sudden outburst of popular interest in supercharging, which gives rise to the question as to why so ancient and so well known a means of increasing the power output of an engine has not been employed before.

The power output obtainable from an engine depends upon two factors, and upon two factors alone:

(1) The weight of air it can consume per minute.

(2) The efficiency at which that air is utilized.

For reasons which will be explained later, we can only afford to supercharge an "efficient" engine; therefore, we must first define carefully just what we mean by an "efficient" engine.

The term "efficiency" is very widely abused. In the best circles it is taken to mean the proportion of the available heat of the fuel which is turned into actual power. Even this definition is not strictly correct, for it presupposes that the fuel is given sufficient air to burn it completely, which is seldom, if ever, the case. Efficiency should be reckoned, not on the fuel, but rather on the air consumed, for every pound of air when carbureted and burned, will liberate a definite quan-

tity of heat, in round figures about 1300 B.t.u., almost regardless of whether it is saturated or supersaturated with fuel. At first sight, this may appear a subtle distinction, but from many points of view it is a most important one, and when considering supercharging it becomes a vital one.

An engine which will give out one brake horsepower for every $7\frac{1}{2}$ pounds of air it consumes per hour, corresponding to a thermal efficiency of 26 per cent, may be classed as a fairly efficient engine regardless of its fuel consumption. The correct ratio of air to fuel is approximately as 15 to 1, so that if there is no waste of fuel, such an engine should consume 1/2 pound of gasoline per horsepower per hour. Supposing, however, that the carburetor were badly adjusted, or the distribution at fault, the same engine might easily consume 3/4 instead of 1/2 pound per horsepower per hour, but its true efficiency would still be unaltered; it would mean only that the additional fuel was being wasted through some fault in the carburetor or distribution system, not that the engine was any less efficient in the true sense of the word. Modern requirements in the way of flexibility and acceleration put such severe demands upon the carburetor and distribution system that it is necessary to employ a somewhat rich mixture setting, and therefore under most conditions we waste a certain amount of fuel, added to which the volatility of the fuel has steadily depreciated; hence the improvement in fuel consumption is by no means commensurate with

the improvement in efficiency which has been realized in recent years.

The limit of power we can get from any engine is reached when either:-

(1) The speed of revolution becomes so high as to prove mechanically destructive.

(2) The flow of waste heat becomes greater than that with which we can cope.

For any given efficiency, the power of an engine is directly proportional to the weight of air we can make it consume per hour. Obviously, we can double the power output of any engine either by doubling the speed or by doubling the pressure at the carburetor. In either case, the engine will take in twice as much air per hour, but in either case we shall bump heavily against one or other of the two limits just mentioned. Increasing the pressure, i.e., supercharging, puts up the heat-flow very rapidly but does not greatly increase the dynamic stresses. Increasing the speed increases the heat-flow somewhat less rapidly but intensifies the dynamic stresses excessively.

In our search for greater power output, we may attempt an increase in speed or in pressure, and the choice will depend upon that one of the two limitations to which we are already nearest.

Broadly speaking, we shall find that in an engine of large cylinder capacity our nearest limit to-day is set by heat-flow, and our best chance of improvement lies in increase of speed,

while in an engine of small capacity the reverse is usually the case and supercharging gives the greater scope.

Let us next consider the relationship between heat-flow and efficiency. In the first place it can not be emphasized too strongly that it is the flow of waste heat, and waste heat alone, which does all the damage in the way of burning out exhaust valves, carbonization, gummed rings and all the other kindred evils to which the inefficient engine is heir.

Let us take the case of two engines, each of the same cylinder capacity, of which the efficiencies, defined in the manner explained above, are 20 per cent and 30 per cent, respectively. Let us assume that, at the same speed, each engine consumes the same weight of air, and that the potential heat equivalent of this quantity of air when fully carbureted amounts to 100 horsepower in either case. Now the first engine will clearly develop 20 B.HP. and let loose 80 horsepower worth of waste heat, while the second will develop 30 B.HP. and turn loose 70 horsepower worth of waste heat. In an engine of this size and of good average design, with reasonably well-cooled exhaust-valve seats, etc., 80 horsepower is just about the utmost limit of waste heat it can digest for any length of time without getting into serious trouble. In the case, therefore, of the 20 per cent efficient engine, 20 B.HP. is the utmost we can hope to get out of it without running up against our second limit, and we certainly could not afford to supercharge. In the case of the 30 per cent effic-

ient engine we can get 30 B.HP. and still have only 70 horsepower worth of waste heat to cope with, and, moreover, it is heat at lower temperature and therefore much less damaging. We have said that we can cope with 80 horsepower worth of waste heat, so that in this case we are not up to our limit and could afford to supercharge the engine up to well over 35 B.HP. and still be exactly in the same position as regards heat limitations as in the case of the less efficient engine when developing 20 B.HP.

Actually, we could go very considerably higher because, in a car, the occasions when we should want 35 B.HP. are obviously much less frequent than our demands for 20 B.HP., so that we should really be quite safe in supercharging the more efficient engine up to 40 B.HP.

The effect, therefore, of increasing the true thermal efficiency from 20 percent to 30 percent is that we have increased the limiting power at the same speed from 20 to 40 B.HP., still keeping the same degree of reliability and maintenance of tune, and have made supercharging possible, which it certainly would not have been in the previous case.

When both engines are running along on the level at the same speed and developing, say, 10 B.HP., the low-efficiency engine is pouring out a steady 40 horsepower worth of waste heat, while the more efficient engine when running at the same power will be turning out only 70/3, or 23.3 HP., and will therefore

last far longer without overhaul or decarbonizing, so that on the comparatively rare occasions on which full power is required we could afford to increase the waste-heat flow to considerably over 80 HP. and still retain at least as good reliability and maintenance of tune. Taking everything into consideration, we should probably be perfectly safe in boosting the more efficient engine up to at least 50 B.HP.

The improvement in thermal efficiency, due to the better knowledge now available, has resulted in quite an extraordinary increase in power output, with the result that even without supercharging the 2-liter engine of to-day gives very nearly, if not quite, as much power as the 4-liter engine of ten years ago, or the 6-liter engine of fifteen years ago, although the external design does not appear to have undergone any conspicuous change.

Little or nothing is known about supercharging to-day which was not common knowledge twenty or thirty years ago. Then as to-day, it was perfectly well known that the power output of an engine was directly proportional to the pressure of the carburetor, and could be increased pro rata with that pressure by supercharging. Then, as to-day, blowers of the Roots or vane type were well known and in regular commercial use. The only new factor which has emerged is that it is only within the last few years that engines have been produced of which the thermal efficiency is high enough to permit of supercharging.

The car engine of ten years ago would hardly stand the full

normal atmospheric pressure, and was either deliberately or inadequately throttled at the valves, carburetor, or both. As the efficiency improved, so the breathing capacity of engines was increased, until to-day it is so high that we can afford even to add to the normal atmospheric pressure; in other words, to supercharge; but it must not be supposed that because one engine of good modern design will stand supercharging, another of inferior design will do likewise. To tack a supercharger on to an inefficient engine is merely to court disaster.

Broadly speaking, the position to-day is that the best designed engines have very nearly reached the limit of speed attainable in the present state of the art, but are well within the limit of heat-flow; hence, the obvious step is to supercharge them if we are striving to get the utmost out of a given cylinder capacity. Who can say what the future will bring? It may quite well be that the trend of improvement will be in the direction of further increase in speed, and that we shall again reach the limit set by heat-flow without supercharging. This will be a more healthy development, for the supercharger is an added complication, and, as such, is always undesirable. Moreover, supercharging greatly increases the tendency to detonate, and therefore tends to lower the efficiency; while a corresponding increase in speed tends to reduce detonation, and so permits us to increase the efficiency. The author's view is therefore that supercharging for motor cars is somewhat of a

passing phase made possible at the moment because, in the race for improvement, the thermodynamic side has moved more rapidly than the mechanical; moreover, it has been stimulated by artificial conditions, such as racing rules and taxation.

Torque Recoil

When we have reached - if, indeed, we ever shall reach - the limit of compression and the limit of speed, and have suppressed all torsional and other dynamic vibration, what then? We can eliminate almost all engine noise audible to the passengers by really careful cam design or by the use of sleeve valves and by careful insulation of the engine. We can, the author contends, eliminate practically all dynamic vibration by the use of six cylinders with a central flywheel, and we can almost, if not quite, eliminate all combustion shock by proper control of the rate of burning - the one factor we are left with, and it is a very important one, is torque recoil. We can do something to mitigate the effects of torque recoil by the use of a sprung and damped engine mounting, and, of course, by increasing the number of cylinders, but the author is tempted to suggest that the most promising line of development lies in the use of two crank shafts rotating in opposite directions, so that the torque reaction is self-contained within the structure of the engine in much the same manner as the reactions of the two opposing couples are self-contained within the structure of a four- or six-cylinder engine.

Some five and twenty years ago that great pioneer, Dr. Lanchester, produced a car, very famous in its day, in which he used a two-cylinder horizontally-opposed engine with two crank shafts in reverse rotation. Though it had but two cylinders, and those of very large size, the smoothness of running was remarkable. Later Lucas produced a two-cycle engined car also with reverse rotation.

With the advent of four- and six-cylinder engines, however, torque recoil was greatly reduced, and faded into a minor evil beside torsional vibration, harshness, etc.

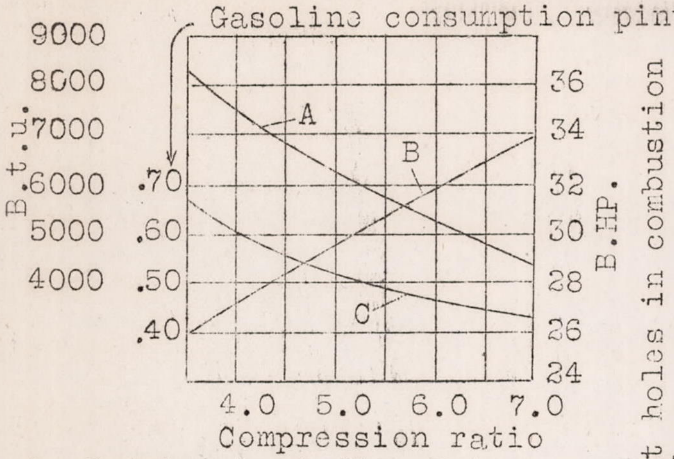
Gradually and progressively we have doctored most of these ills, but torque recoil remains, and becomes the more noticeable feature as other complaints are healed, and the more aggressive as the use of closed bodies increases. To-day the author thinks that the time is ripe, or nearly ripe, to reconsider the use of reverse rotation for the more luxurious types of pleasure cars.

With center flywheels on each crank shaft and double helical gearing adjacent to the flywheels, we could get rid of any gear noise, and in this manner, the author suggests, lies the possibility of producing an engine of which the existence could scarcely be felt.

Research

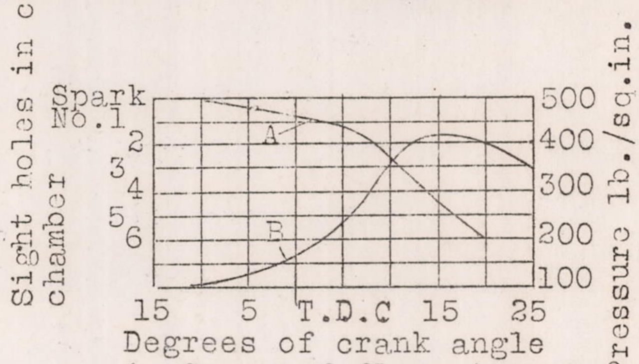
In conclusion, the author stressed the need of interpreting for manufacturers the products of research. In spite of our

starved resources, the work carried out by our Government establishments and universities was more imaginative and productive than that of other countries. This was not the case, however, with the automobile trade, where research was regarded with grave suspicion, which contrasted adversely with Continental practice. British research was followed and applied on the Continent and in America, and subsequently copied in England. There was a lag of from three to five years between the foreigner's appreciation and our own of the value of British research.



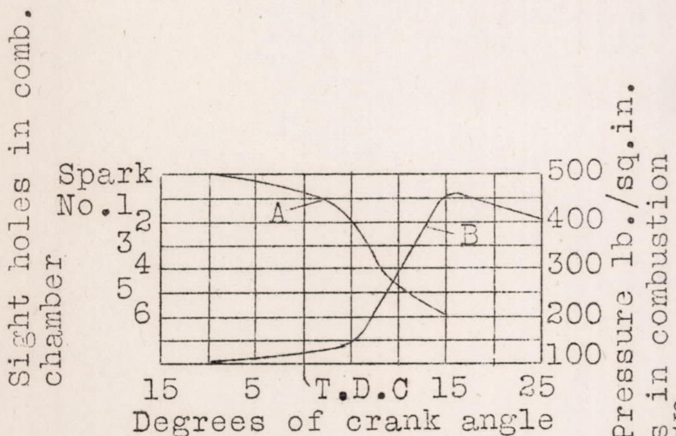
A, Surplus heat flow B.t.u.per B.HP.-hr.
B, B.HP. at 1500 R.P.M.
C, Pints per B.HP.-hr.

Fig.1 Variation in B.HP. fuel consumption and surplus heat flow with different compression ratios.



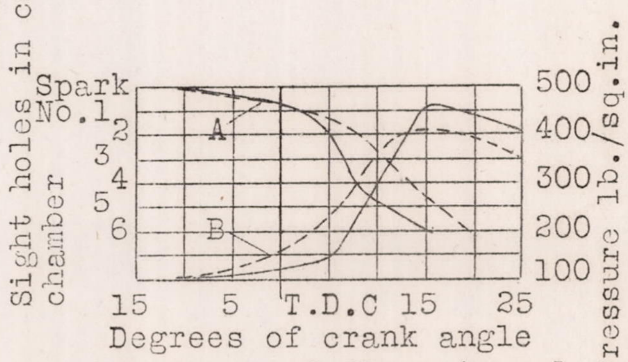
A, Curve of flame travel
B, Pressure lb./sq.in.

Fig.4 Curves of observed spread of flame and pressure rise.



A, Curve of flame travel
B, Pressure lb./sq.in.

Fig.5 Similar curves to those shown in Fig.4, but for different type of head.



A, Curve of flame travel
B, Pressure lb./sq.in.

Fig.6 The curves shown in Figs.4 & 5 superimposed.

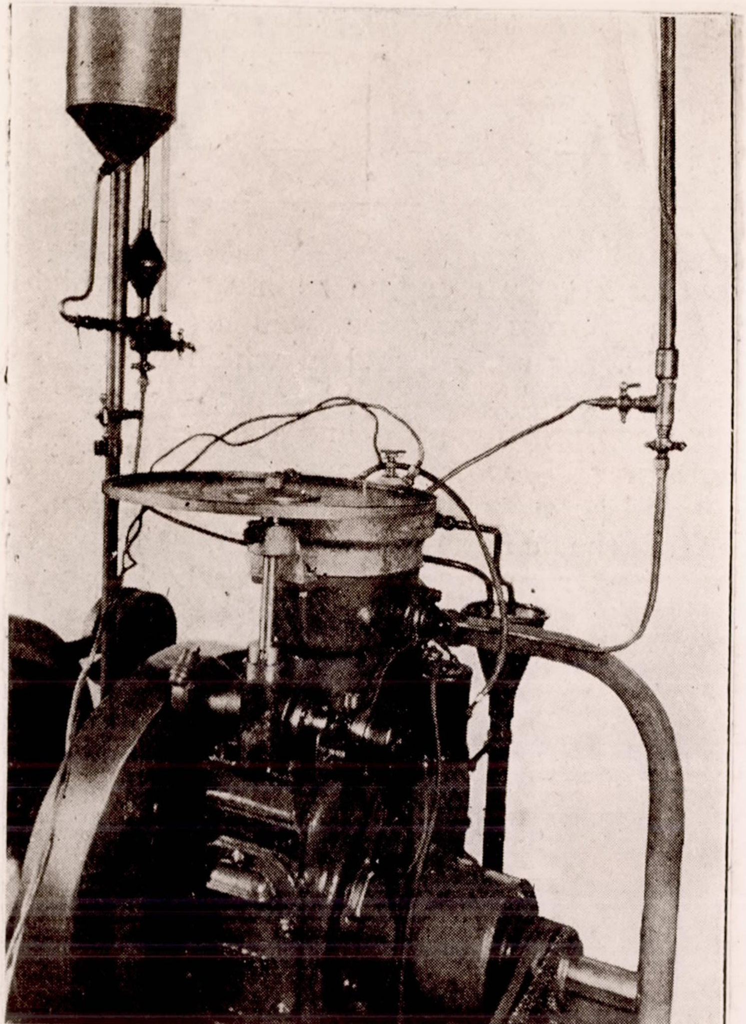


Fig. 2.
Experimental engine for investigating flame spread and pressure-rise in the combustion chamber.

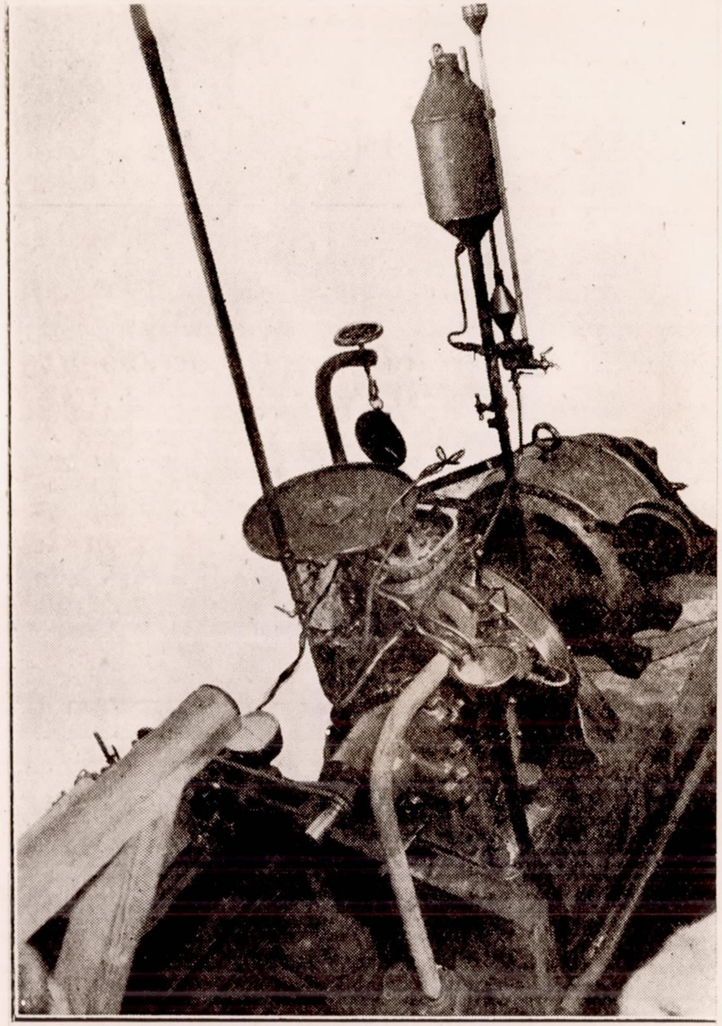


Fig. 3.
Another view of the experimental engine shown in Fig. 2.

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Curve A. Pressure rise 22.6 lb/sq.in. per deg.Max press. 429 lb./sq.in.

Curve B. Pressure rise 60.3 lb./sq.in. per deg.Max press. 451 lb./sq.in.

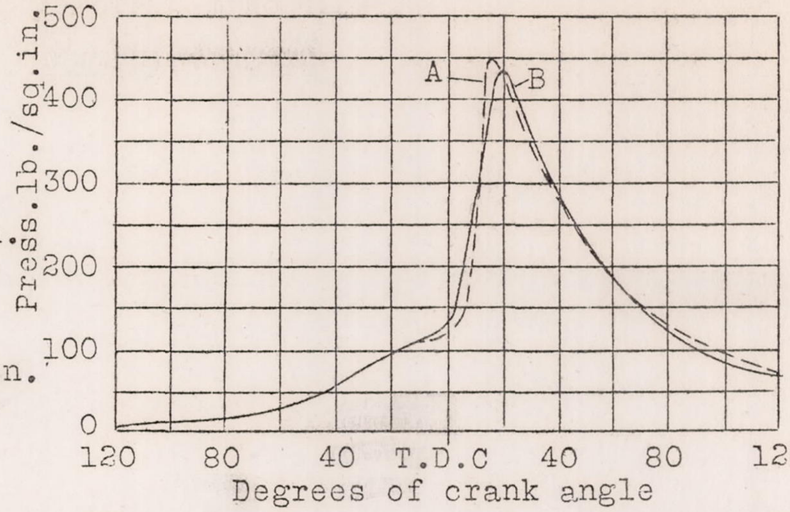

Fig.7 Two indicator diagrams showing normal and unduly rapid burning.

A, C.R. 4.92:1
B, C.R. 4.95:1
C, C.R. 4.88:1

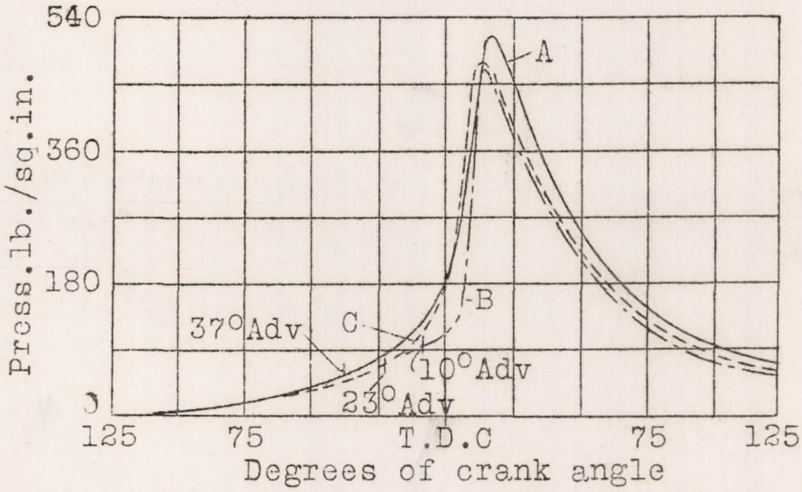

Fig.8 Three indicator diagrams taken with varying degrees of turbulence.

a, 34°=0.00375 sec.
b, 41°=0.0045 "
c, 49°=0.0054 "
A, R=6.0:1 I.M.E.P. =146.5 lb./sq.in.
B, R=5.0:1 I.M.E.P. =136 lb./sq.in.
C, R=4.0:1 I.M.E.P. 120 lb.sq.in.

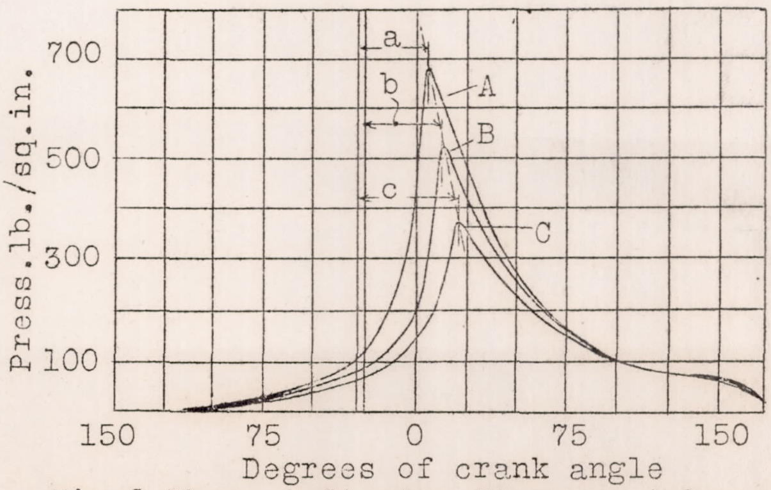

Fig.9 Three indicator diagrams taken with varying compression.